# BARYON-MESON INTERACTIONS IN CHIRAL QUARK MODEL*

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Using the resonating group method (RGM), we dynamically study the baryon-meson interactions in chiral quark model. Some interesting results are obtained: (1) The $\Sigma K$ state has an attractive interaction, which consequently results in a $\Sigma K$ quasibound state. When the channel coupling of $\Sigma K$ and $\Lambda K$ is considered, a sharp resonance appears between the thresholds of these two channels. (2) The interaction of $\Delta K$ state with isospin $I = 1$ is attractive, which can make for a $\Delta K$ quasibound state. (3) When the coupling to the $\Lambda K^*$ channel is considered, the $N\phi$ is found to be a quasibound state in the extended chiral SU(3) quark model with several MeV binding energy. (4) The calculated $S$-, $P$-, $D$-, and $F$-wave $KN$ phase shifts achieve a considerable improvement in not only the signs but also the magnitudes in comparison with other's previous quark model study.

## 1. Introduction

Nowadays people still need QCD-inspired models to study the non-perturbative QCD effects in the low-energy region. Among these models, the chiral SU(3) quark model has been quite successful in reproducing the energies of the baryon ground states, the binding energy of deuteron, the $NN$ scattering phase shifts, and the $NY$ (nucleon-hyperon) cross sections. Inspired by these achievements, we try to extend this model to study the baryon-meson systems. In order to study the short-range feature of the quark-quark interaction in the low-energy region, we further extend our chiral SU(3) quark model to include the vector meson exchanges. The OGE that dominantly governs the short-range quark-quark interaction in the original chiral SU(3) quark model is now nearly replaced by the vector-meson exchanges. We use these two models to study the baryon-meson interactions.

In this paper, we show the RGM dynamical calculating results of the $\Lambda K$, $\Sigma K$, $\Delta K$, $N\phi$, and $KN$ states obtained in the chiral SU(3) quark model as well as in the extended chiral SU(3) quark model [1,2,3,4,5].

## 2. Formulation

The chiral SU(3) quark model and the extended chiral SU(3) quark model have been widely described in the literature [1,2,3,4], and we refer the reader to those works for details. Here we just give the salient features of our chiral quark model.

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In the chiral quark model, the total Hamiltonian of baryon-meson systems can be written as

$$H = \sum_{i=1}^{5} T_i - T_G + \sum_{i<j=1}^{4} V_{ij} + \sum_{i=1}^{4} V_{i\bar{5}}, \tag{1}$$

where $T_G$ is the kinetic energy operator for the center-of-mass motion, and $V_{ij}$ and $V_{i\bar{5}}$ represent the quark-quark and quark-antiquark interactions, respectively,

$$V_{ij} = V_{ij}^{OGE} + V_{ij}^{conf} + V_{ij}^{ch}, \tag{2}$$

where $V_{ij}^{ch}$ is the chiral fields induced effective quark-quark potential. In the chiral SU(3) quark model, $V_{ij}^{ch}$ can be written as

$$V_{ij}^{ch} = \sum_{a=0}^{8} V_{\sigma_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\pi_a}(\boldsymbol{r}_{ij}), \tag{3}$$

and in the extended chiral SU(3) quark model, $V_{ij}^{ch}$ can be written as

$$V_{ij}^{ch} = \sum_{a=0}^{8} V_{\sigma_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\pi_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\rho_a}(\boldsymbol{r}_{ij}). \tag{4}$$

$V_{i\bar{5}}$ in Eq. (1) includes two parts: direct interaction and annihilation parts,

$$V_{i\bar{5}} = V_{i\bar{5}}^{dir} + V_{i\bar{5}}^{ann}, \tag{5}$$

with

$$V_{i\bar{5}}^{dir} = V_{i\bar{5}}^{conf} + V_{i\bar{5}}^{OGE} + V_{i\bar{5}}^{ch}. \tag{6}$$

The annihilation interaction $V_{i\bar{5}}^{ann}$ is not included in baryon-meson interactions since they are assumed not to contribute significantly to a molecular state or a scattering process, which is the subject of our study.

Table 1. Model parameters. $\Lambda$ = 1100 MeV, $m_u$ = 313 MeV, $m_s$ = 470 MeV, $g_{ch}$ = 2.621, $b$ = 0.5 fm for set I and 0.45 fm for sets II and III. The meson masses are taken to be the experimental data except for $m_\sigma$.

| | $m_\sigma$ (MeV) | $g_{chv}$ | $f_{chv}/g_{chv}$ | $g_u^2$ | $g_s^2$ | $a_{uu}^c$ (MeV/fm$^2$) | $a_{us}^c$ (MeV/fm$^2$) | $a_{ss}^c$ (MeV/fm$^2$) |
|---|---|---|---|---|---|---|---|---|
| I | 595 | – | – | 0.766 | 0.846 | 46.6 | 58.7 | 99.2 |
| II | 535 | 2.351 | 0 | 0.056 | 0.203 | 44.5 | 79.6 | 163.7 |
| III | 547 | 1.973 | 2/3 | 0.132 | 0.250 | 39.1 | 69.2 | 142.5 |

The model parameters can be fitted by several conditions, e.g. the energies of baryons, the binding energy of deuteron, the chiral symmetry, and the stability conditions of baryons. We listed them in Table 1, where the first set is for the chiral SU(3) quark model, the second and third sets are for the extended chiral SU(3) quark model. All these three sets of parameters can give a reasonable description of the $NN$ phase shifts [6].

## 3. Results and Discussion

### 3.1. $\Lambda K$ and $\Sigma K$ States

The nucleon resonance $S_{11}(1535)$ is explained as an excited three quark state in the traditional constitute quark model [7,8]. But on the hadron level, it is explained as a $\Lambda K$-$\Sigma K$ quasibound state [9,10]. A dynamical study on a quark level of the $\Lambda K$ and $\Sigma K$ interactions will be useful to get a better understanding of the $S_{11}(1535)$ [1].

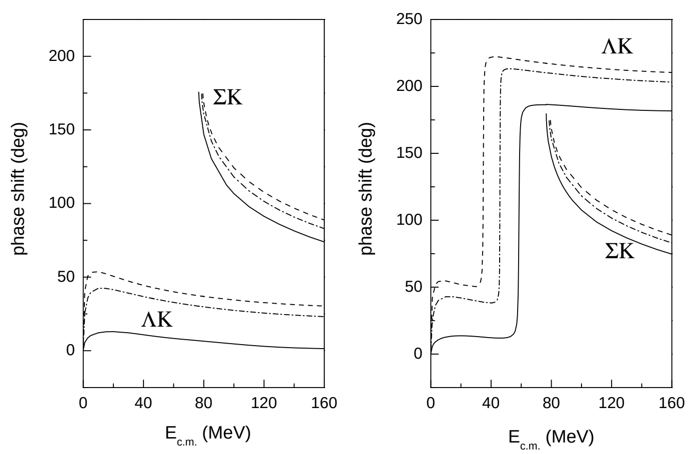


Figure 1. $S$-wave $\Lambda K$ and $\Sigma K$ phase shifts in one-channel and coupled-channel calculation. The solid curves represent the results obtained in the chiral SU(3) quark model. The dashed and dash-dotted curves show the results from the extended chiral SU(3) quark model by taking $f_{chv}/g_{chv}$ as 0 and 2/3, respectively.

Fig. 1 shows the $S$-wave $\Lambda K$ and $\Sigma K$ phase shifts in one-channel (left) and coupled-channel (right) calculations. The phase shifts show that there is a strong attraction of $\Sigma K$, which can make for a $\Sigma K$ quasibound state, while the interaction of $\Lambda K$ is comparatively weak. When the channel coupling of $\Lambda K$ and $\Sigma K$ is considered, the phase shifts show a sharp resonance between the thresholds of these two channels. The spin-parity is $J^P = 1/2^-$ and width $\Gamma \approx 5$ MeV. The narrow gap of the $\Lambda K$ and $\Sigma K$ thresholds, the strong attraction between $\Sigma$ and $K$, and the sizeable off-diagonal matrix elements of $\Lambda K$ and $\Sigma K$ are responsible for the appearance of this resonance. The final conclusion regarding what is the resonance we obtained and its exact theoretical mass and width will wait for further work where more channels will be considered.

### 3.2. $\Delta K$ State

The $\Delta K$ state has first been studied on the hadron level [11]. We perform a RGM dynamical study of the structures of $\Delta K$ state within our chiral quark model [2]. Fig.

2 shows the diagonal matrix elements of the Hamiltonian in the generator coordinate method (GCM) calculation, which can describe the $\Delta K$ interaction qualitatively.

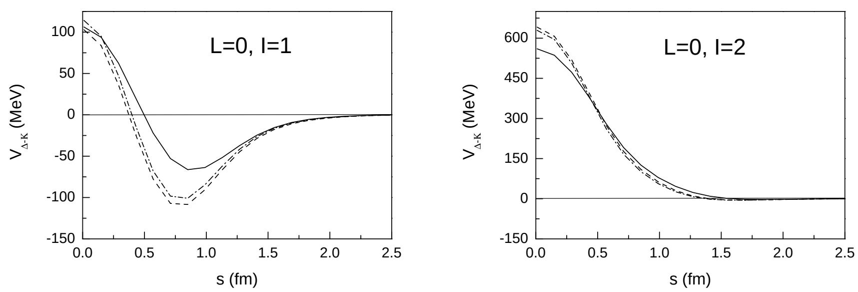


Figure 2. The GCM matrix elements of the Hamiltonian for $\Delta K$. Same notation as in Fig. 1.

From Fig. 2 one sees that the $\Delta K$ interaction is attractive for isospin $I = 1$ channel, while strongly repulsive for $I = 2$ channel. The attraction can result in a $\Delta K$ bound state with a binding energy of about 3, 20, and 15 MeV by using three different sets of parameters. To examine if $(\Delta K)_{LSJ=0\frac{3}{2}\frac{3}{2}}$ is possible to be a resonance or a bound state, the channel coupling between $(\Delta K)_{LSJ=0\frac{3}{2}\frac{3}{2}}$ and $(NK^*)_{LSJ=0\frac{3}{2}\frac{3}{2}}$ would be considered in our future work.

### 3.3. *$N\phi$ State*

It has been reported that the QCD van der Waals attractive potential is strong enough to bind a $\phi$ meson onto a nucleon to form a bound state [12]. We try to study the possibility of a $N\phi$ bound state in our chiral quark model [5]. Table 2 shows the calculated binding energy of $N\phi$.

Table 2. The binding energy of $N\phi$.

| | One-channel | | Coupled-channel | |
|---|---|---|---|---|
| | $S = 1/2$ | $S = 3/2$ | $S = 1/2$ | $S = 3/2$ |
| I | – | – | – | – |
| II | 1 | 3 | 3 | 9 |
| III | – | – | 1 | 6 |

From Table 2 one sees that in the one channel study, one can get a bound state only by using the second set of parameters. When the channel coupling to $\Lambda K^*$ is considered, the $N\phi$ is found to be a bound state in the extended chiral SU(3) quark model with several MeV binding energy. Further the tensor force will be considered in the future work, which would make a bigger binding energy.

For the $N\phi$ system, the two color-singlet clusters have no quark in common. The attractive interaction is dominantly provided by $\sigma$ exchange. Thus $N\phi$ is an ideal place to test the strength of the coupling of the quark and $\sigma$ chiral field.

### 3.4. *KN Scattering*

The $KN$ scattering has aroused particular interest in the past. But most of the works on the quark level cannot give a reasonable description of the $KN$ phase shifts up to $L = 3$. We dynamically study the $KN$ scattering in our chiral quark model [3,2,4]. When $m_\sigma$ is chosen to be 675 MeV and the mixing of $\sigma_0$ and $\sigma_8$ is considered, we can get a satisfactory description of the $S$-, $P$-, $D$-, and $F$-wave $KN$ phase shifts (see Figs. 1-4 in Ref. 4). The results from the chiral SU(3) quark model and the extended chiral SU(3) quark model are quite similar although the short-range interaction mechanisms in these two models are quite different. Compared with the results in other's previous quark model study [13], our theoretical phase shifts achieve correct signs for several partial waves and a considerable improvement in the magnitude for many channels.

## 4. Summary

We dynamically study the baryon-meson interactions in chiral quark model by using the RGM. Some interesting results are obtained: (1) The $\Sigma K$ state has an attractive interaction, which consequently results in a $\Sigma K$ quasibound state. When the channel coupling of $\Sigma K$ and $\Lambda K$ is considered, a sharp resonance appears between the thresholds of these two channels. (2) The interaction of $\Delta K$ state with $I = 1$ is attractive, which can make for a $\Delta K$ quasibound state, while for $I = 2$ channel, the interaction is strongly repulsive. (3) When the coupling to the $\Lambda K^*$ channel is considered, the $N\phi$ is found to be a quasibound state in the extended chiral SU(3) quark model with several MeV binding energy. (4) The calculated $KN$ phase shifts achieve a considerable improvement in not only the signs but also the magnitudes in comparison with other's previous quark model study.

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